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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1141

AN ANALYSIS OF THE AIRSPEEDS AND NORMAL ACCELERATIONS
OF BOEING S-307 AIRPLANES IN COMMERCIAL
TRANSPORT OPERATION

By A. M. Peiser and W. G. Walker

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

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AN ANALYSIS OF THE AIRSPEEDS AND NORMAL ACCELERATIONS OF BOEING S-307 AIRPLANES IN COMMERCIAL TRANSPORT OPERATION

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SUMMARY

Acceleration and airspeed data in the form of V-G records from three Boeing S-307 airplanes operated by Pan American Airways have been analyzed to determine the effects of prewar and war operation and of the season of the year on the applied loads experienced during commercial transport operation. Greater loads were found to be imposed on the airplanes during the war period than during the prewar period. Flights during the war period were generally made through regions of greater turbulence, and operating speeds in this period were less conservative. No significant differences were determined among the data for seasonal operation within the war period. Operating speeds, however, tended to be more conservative during the months of July, August, and September.

INTRODUCTION

Data on the applied loads of commercial airplanes are being collected at the Langley Memorial Aeronautical Laboratory of the NACA in cooperation with the Civil Aeronautics Authority and the commercial airlines of the United States. These data are obtained by means of the NACA V-G recorder (reference 1) and, up to the present time, records representing about 200,000 hours of operation over a period of about 12 years have been collected. Large quantities of data are available, therefore, for use in evaluating the actual flight loads imposed on commercial transport airplanes and in determining the

effect of airplane characteristics, operating speeds, terrain, and season on the applied loads for which the wing structures of new airplanes must be designed.

The over-all picture of airspeed and acceleration for transport airplanes is presented in reference 2 in the form of composite V-G envelopes for several airplanes operating in various parts of the world. Presentation of the data in this form, however, evidently contributes little to the determination of the significant factors affecting the imposed loads or to the prediction of the future accelerations that will be experienced by transport airplanes. In order to determine significant factors and to predict trends, methods of analyzing the V-G data that would take these problems into account had to be developed. Recent attempts to develop such methods have led to the utilization of simple statistical procedures that predict the accelerations experienced by transport airplanes with a high degree of accuracy (reference 3).

The present paper has been prepared to give the results of the analysis of the V-G records obtained from three Boeing S-307 airplanes operating in the Caribbean region and the northern part of South America during the period from 1940 to 1944. The data have been analyzed to indicate the influences of prewar and war operation and of seasonal operation on the applied loads experienced during commercial transport operation.

SCOPE AND EVALUATION OF DATA

A total of 311 V-G records representing 17,095 hours of flight was available for the present analysis. These records were obtained from three S-307 airplanes operated by Pan American Airways during the period from April 1940 to September 1944 in the Caribbean region and the northern part of South America. The records were supplied to the Langley Memorial Aeronautical Laboratory of the NACA by PAA together with the dates of installation and removal, the number of flight hours per record, the routes flown during the time the record was installed in the airplane, and occasional supplementary remarks regarding unusual atmospheric conditions or operating practices.

Because little or no information was made available on the operating weight and other characteristics of the airplane pertinent to the present analysis, the values obtained from references 2 and 4 have been used throughout. These values are presented in table I. Since estimates of the maximum level-flight speed of the airplane differed for different altitudes and different estimators from about 235 to 260 miles per hour, 250 miles per hour seemed a reasonable figure. The limit load factor of 3.25g was determined from the other airplane characteristics on the basis of the requirements set forth in reference 5. This value represents the acceleration that would result from an effective gust velocity of 30K feet per second encountered at the maximum level-flight speed of 250 miles per hour, where K is the gust alleviation factor (reference 5). Based on the design gross weight of the S-307 airplane, $K = 1.125$ has been used herein.

In several cases, the records were obtained during the course of pilot check flights and, inasmuch as the accelerations evaluated from these records were almost certainly due to maneuvers and could not be regarded as typical of normal transport operation in turbulent air, six such records, totaling 27 hours of flight were rejected. There were 305 records totaling 17,068 hours of flight that, on the basis of the information supplied, could be regarded as suitable for the present analysis. The flight time on these records varied from 3 hours to 268 hours. Because the method of analysis employed requires that the flight time per record be held reasonably uniform, and because about 90 percent of the records represented less than 120 hours of flight, the statistical analysis was limited to these records. The choice of a suitable range of flight hours is somewhat arbitrary. The present choice, however, conforms to the statement given in reference 3 of the ranges that are desirable in the application of the present method of analysis. A summary of the records supplied, the records suitable for analysis, and the records used in the analysis is given in table II.

The bulk of the data has been compiled since the entry of the United States into World War II, so that the investigation of seasonal effects has been limited to the period from January 1942 to September 1944. For convenience in the analysis of seasonal effects, the year was divided into four 3-month periods and each record was associated with the period that most closely

corresponded to its installation and removal dates. The period from January to March will be referred to as season I, the period from April to June as season II, and so on. In table II, a breakdown is given of the number of records and flight hours used in the analysis according to prewar and war operation and according to seasonal operation within the war period.

In the analysis, no attempt has been made to classify acceleration peaks as due to gusts, gust-maneuvers, or maneuvers. Such a classification is, at best, highly uncertain. Because evidence of the past indicates, however, that the main source of applied loads experienced in commercial transport operation is the atmospheric gust, and because most of the available records are essentially symmetric with respect to positive and negative acceleration increments, the assumption that all large accelerations are due to gusts seems quite reasonable.

METHODS OF ANALYSIS AND RESULTS

The V-G data have been analyzed in accordance with the methods of reference 3. From each record, six quantities were read: the flight time, the maximum indicated airspeed V_{\max} , the maximum positive and negative acceleration increments Δn_{\max} , and the indicated airspeeds V_0 at which these maximum accelerations were experienced. The frequency distributions of V_{\max} , Δn_{\max} , and V_0 for the prewar and war periods are shown in table III. The frequency distributions of V_{\max} and Δn_{\max} for the four seasons within the war period are shown in table IV. Because of the essential symmetry of positive and negative acceleration increments, values of Δn_{\max} were combined without regard to sign.

The mean value \bar{V}_{\max} , $\bar{\Delta n}_{\max}$, or \bar{V}_0 , the standard deviation σ , and the coefficient of skewness α for each of the distributions (reference 6) have been computed and the results are shown in tables III and IV. With the use of these computed values and the procedure outlined in reference 3, Pearson Type III probability curves can be fitted to each of the frequency distributions so that estimates may be made of the probabilities P_V and $P_{\Delta n}$, respectively, that given values of airspeed

and acceleration will be exceeded and of the probability P_0 that the maximum acceleration increment on a record will occur in a given speed range. (Probability may be interpreted herein as the ratio of the number of records satisfying a given condition to the total number of records.)

From the values of P_v and $P_{\Delta n}$ and the average record time τ for the records used in the analysis, estimates may be made of the average number of airspeeds and accelerations that will exceed given values in a stated number of flight hours. In fact, according to the foregoing interpretation of probability, an average of one in $1/P_v$ records will have an airspeed exceeding a given value and $1/P_{\Delta n}$ records will have a positive and a negative acceleration increment exceeding a given value. Thus, on the average, one airspeed exceeding the given value will be experienced in τ/P_v hours and one positive and one negative acceleration increment exceeding the given value will be experienced in $\tau/P_{\Delta n}$ hours.

With the use of the values of τ in table II, the average number of hours required to exceed different values of airspeed and acceleration have been computed by the method just described for prewar, war, and seasonal operation. In figures 1 and 2 the results for airspeed and acceleration, respectively, are shown for prewar and war operation, and in figures 3 and 4 similar results are shown for seasonal operation within the war period. It should be noted that the curves of figures 1 to 4 are merely Pearson Type III probability curves referred to a time scale. The average times required to exceed the design load-factor increment of 2.25g and the maximum level-flight speed of 250 miles per hour of the S-3C7 airplane have been summarized in table V.

The analysis up to this point does not include the speeds at which the various acceleration increments are experienced. This factor must be considered if, under the assumption of the gust condition, the magnitudes of the critical gusts encountered during transport operation are to be determined. A convenient method of presenting the necessary information is in the form of the "flight envelope" (reference 3), which predicts that, on the average, in a given number of flight hours, one airspeed will exceed the envelope and one positive and one negative acceleration increment will exceed the envelope with equal

probability of being experienced at any airspeed. The construction of the flight envelope involves the use of the probabilities P_v , $P_{\Delta n}$, and P_o , and the methods of construction are explained in reference 3. In figure 5, the calculated flight envelope for 2500 hours of flight for prewar operation is compared with the composite V-G envelope for 2540 hours, representing all the available records for prewar operation. Also shown in figure 5 are the calculated flight envelopes for 10,000, 20,000, and 50,000 hours of flight. The corresponding calculated flight envelopes for war operation are compared in figure 6 with the composite V-G envelope for 14,528 hours, representing all the available records for war operation.

The 50,000-hour flight envelopes for the prewar and war period are compared in figure 7. Also shown in this figure is the envelope of the present design gust requirements set forth in reference 5. This envelope is based upon an effective gust velocity of 30K feet per second at maximum level-flight speed and 15K feet per second at maximum gliding speed, where K is the gust-alleviation factor (reference 5). The acceleration increments corresponding to lift coefficients greater than the steady-flight maximum lift coefficient in figure 7 are felt to be real. Their presence can be ascribed to either air-speed installation errors of unknown magnitude or to dynamic lift effects such as are indicated in reference 7.

The flight envelopes have been converted, by means of the sharp-edged-gust formula (reference 1), to gust-velocity envelopes which predict that, on the average, in a stated number of hours of flight, one up gust and one down gust will exceed the envelope with equal probability of being encountered at any airspeed. In figures 8 and 9, the gust-velocity envelopes corresponding to the calculated flight envelopes of figures 5 and 6, respectively, are presented.

PRECISION OF DATA

Laboratory tests of the NACA V-G recorder have indicated that inherent errors in the instrument would not exceed $\pm 0.2g$ for acceleration and 3 percent of the full-scale value for airspeed. Experience has shown that the possible errors in any particular installation are dependent

upon the experience of the operator and will vary over wide limits. In the evaluation of the V-G data, the practice has been to inspect all incoming records in order to maintain a check on installation and to reduce human errors to a minimum. Inasmuch as the present analysis covers a long period of time and involves numerous V-G recorders installed in several airplanes, the probability that the instrument errors are random suggests that the errors in the statistical analysis are considerably less than the values given.

The use of the sharp-edged-gust formula for the conversion of airspeed and acceleration data from one type of airplane to a form suitable for application to other aircraft requires that the weight of the airplane be known at the time the accelerations are experienced. Since no precise information concerning the operating weights of the S-307 is available, the design gross weight has been used in the calculation of effective gust velocities. Scheduled operating hours, which were supplied by PAA, have been used as the basis of a calculation of the average gross weight of the airplane during any flight and it appears that, on the average, the effective gust velocities quoted would be conservative by about 5 percent.

DISCUSSION

Application of the methods of reference 3 to the data from the S-307 airplanes has indicated certain trends with regard to the influences of prewar and war operation and seasonal operation on the applied loads experienced during commercial transport operation. The operating practices within any of these periods may be expressed as a function of such parameters as route, forecasting and dispatching techniques, operating speed, and operating weight. The scope of the present data, however, permits the evaluation of only the effects of forecasting and dispatching technique and operating speed on airplane life. Thus, in the analysis of trends in any particular period of operation, only these parameters will be considered.

The difficult problem in a statistical analysis of this type is the determination of whether significant differences exist among different sets of data. Much

effort has been spent on evolving tests for significant differences that would apply to the V-G data, but at the present time, no definite results can be given. On the basis of the work done to date and past experience in this field, it would appear that, for data of the scope and quantity of the present data, if one probability is greater than the other by a ratio of more than 5 to 1, the differences may be regarded as significant. Further work on this subject is needed before this estimate can be improved.

Forecasting and dispatching technique.- In view of the exigencies of the war period, it seems reasonable to expect that forecasting and dispatching techniques differed considerably during prewar and war operation. Security regulations during the war period hindered the transmittal of meteorological information so that flights in wartime were usually made with much less knowledge of prevailing weather conditions. Also, the increased flying schedules and the necessity of making immediate shipments must inevitably have resulted in some relaxation of dispatching techniques to permit flights under conditions conducive to severe turbulence that may have grounded planes during prewar operation. Comparison of the average number of hours of flight per day for the two periods tends to support the second conclusion. Examination of the flight hours per record and the dates of the installation and the removal of the records from the airplanes showed that during the prewar period the airplanes averaged 4.5 flight hours per day, and during the war period, 8.5 flight hours per day.

For seasonal operation within the war period, the airplanes averaged 8.8, 8.8, 8.1, and 8.5 flight hours per day in seasons I, II, III, and IV, respectively. Thus, if forecasting facilities are assumed to have been the same in each season, there are no apparent differences in dispatching techniques among the seasons.

Operating speed.- Determination of normal operating speeds is not possible from the V-G records alone, and inasmuch as no supplementary information concerning speed was supplied with the records, no precise statements can be made. Average conditions can be inferred, however, from examination of the probability curves for V_{max} (figs. 1 and 3) and from the flight envelopes of figures 5 and 6.

The results in figure 1 indicate that speeds in excess of the design level-flight speed were attained about 20 times as often during the war period as during the prewar period. This fact in itself, as a factor in airplane life, is not particularly significant since the high speeds might very well have been attained during the time that the airplane was flying in smooth air. Average speeds maintained in regions of turbulence may be determined, however, from the speeds in figures 5 and 6, which correspond to the maximum acceleration increments on the flight envelopes. These speeds will be called "probable speeds" herein since they are the speeds at which the largest accelerations will most probably be experienced. Inspection of figures 5 and 6 shows that the probable speed for prewar operation is 145 miles per hour, and for war operation, 165 miles per hour. It thus appears that, during the war period, the airplanes were flown at higher speeds in regions of turbulence than during the prewar period.

For seasonal operations, certain trends are worthy of note. Although figure 3 does not reveal any significant differences in operating speeds among the various seasons, it does suggest that speeds in excess of the design level-flight speed were attained less frequently during season III than during the other seasons. The figures on probable speed in table V for seasonal operations, which were obtained by a breakdown of the V_0 data of table III for the war period, show that, in addition, the airplanes were flown in regions of turbulence at lower speeds during season III.

Prewar and War Operation

The results in figure 2 and table V show that higher values of acceleration were experienced during the war period than during the prewar period. It would appear from table V that, during the war period, the probability of exceeding the limit-load-factor increment of $\pm 2.25g$ was about 2000 times as great as during the prewar period. On the basis of the 5-to-1 criterion for significant differences set forth herein, this difference may be regarded as highly significant. The differences between the two periods are further emphasized in figure 7 in which the 50,000-hour flight envelopes for each of the periods are compared. The

prewar calculated flight envelope is well within the design gust envelope, whereas the calculated flight envelope for the war period exceeds it over a fairly large speed range.

The differences between the two periods can, of course, be explained in terms of the two factors previously discussed, namely, the greater turbulence experienced during the war period (due to restricted forecasting and/or relaxed dispatching techniques) and the higher speeds maintained during the war period in regions of turbulence. It would be desirable to determine the separate effect of each of these factors but such a determination cannot be made on the basis of the present data. As additional information from other transport airplanes becomes available, however, the knowledge gained thereby may be expected to permit a suitable assessment of each of the foregoing factors.

Additional information regarding operations during the prewar and war periods may be obtained from the effective-gust-velocity envelopes of figures 8 and 9. These envelopes have been used to determine the average number of hours required to experience an effective gust velocity greater than 30 feet per second at different airspeeds for the prewar and the war periods. The results are presented in figure 10. The differences in operating practices in the two periods are emphasized in this figure. For example, in the prewar period, an effective gust velocity greater than 30 feet per second would be experienced an average of once in 200,000 hours at the normal cruising speed (200 mph) of the S-307 airplane, and at the same speed during the war period, an average of once in 2,000 hours. These values support the conclusion already drawn that during the war period, the airplanes were flown into regions of turbulence at higher speeds than during the prewar period.

The conclusion that flights were made through more turbulent air during the war period is also strengthened on the basis of figure 10. Examination of the probable speeds (145 mph for the prewar period and 165 mph for the war period) shows that for the prewar period an effective gust velocity of 30 feet per second would be experienced at the probable speed once in 430 hours, and for the war period, once in 140 hours. That is, not only were the airplanes flown in turbulent air at higher speeds, but they were also flown into regions of greater turbulence during the war period.

Seasonal Operation within the War Period

The results in figure 4 and table V indicate that, on the basis of the 5-to-1 criterion set forth herein for significant differences, greater loads would be imposed on the airplane in season I (the months of January, February, and March) than in the other three seasons. The amount and type of data on hand, however, are felt to be such that no definite conclusions can be drawn at the present time. The frequency distributions of table IV show that the difference between season I and the other seasons arises mainly from the four acceleration increments greater than 1.8g that were experienced in season I. The two largest increments were taken from the record that appears as figure 9 in reference 8. This record has been classified as "unusual" in reference 8 in which it was suggested that the outstanding accelerations were experienced largely as a result of control movements. No additional information regarding this record was supplied so that no basis existed for rejecting it in the present analysis. The influence of this record, however, upon the distribution of accelerations for season I, for which a total of only 28 records was available, is such that definite conclusions regarding the trends in figure 9 must await the examination of additional data. Pending the receipt of such data, the differences in the results for season I and the other seasons cannot be regarded as significant. It might be noted that omission of the "unusual" record from the analysis would result in closer agreement among the seasons, but that season I would maintain its present relative position in figure 4.

The more cautious operation in regions of turbulence during season III (the months of July, August, and September) is reflected in figure 4 and table V by the longer times required in this season to exceed large values of acceleration. That this increase can be attributed to the reduction of speed in turbulent air may be demonstrated by the reduction of the limit load factor increment for season III by the ratio of 155 to 165 (the ratio of the probable speed in season III to the probable speed in seasons II and IV) to 2.11g to eliminate the differences in operating speeds. Figure 4 shows that this reduced value would be exceeded an average of once in

2.9×10^5 hours in season III. This result is in extremely good agreement with the average time to exceed the limit load factor increment given in table V for seasons II and IV.

CONCLUSIONS

An analysis was made of the V-G records obtained from three S-307 airplanes during normal transport operation in the Caribbean region and the northern part of South America to determine the effects of pre-war and war operation and of the season of the year on the applied loads experienced during commercial transport operation. The analysis indicated the following conclusions:

1. Larger accelerations were imposed on the S-307 airplane during war operation than during prewar operation. The ratio of the probability of exceeding the limit load factor during the war period to the probability during the prewar period is about 2000 to 1.
2. The airplanes were subjected to higher speeds during the war period than during the prewar period. During the war period, the airplanes exceeded the maximum level-flight speed about 20 times as often as during the prewar period.
3. During the war period, flights were made through turbulence of greater severity than during the prewar period. Despite this fact, higher speeds were usually maintained during the war period in regions of turbulence.
4. No significant differences could be determined, on the basis of the present data, among the airspeed and acceleration data for seasonal operation within the war period. Operating speeds, however, tended to be more conservative during the months of July, August, and September.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., March 19, 1946

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ADDENDUM

Since the preparation of the present paper, an additional 6,083 hours of V-G records obtained with the S-307 airplanes have become available; so far as is known, therefore, all existing data for war operation are now at hand. An opportunity is thus afforded to make a further check of the calculated flight envelopes for war operation given in figure 6. This check is shown in figure 11 in which the composite V-G record for the additional data has been superimposed upon the composite of the original 14,528 flight hours to obtain a new composite for 20,611 flight hours. Also shown in figure 11 is the calculated 20,000-hour flight envelope obtained from figure 6. It may be noted that three positive acceleration increments and one airspeed exceed the envelope.

The calculated envelope in figure 11 predicts that an average of one positive and one negative acceleration increment and one airspeed will exceed the envelope in 20,000 hours of flight. Inasmuch as these predictions are based on average results for large masses of data, the agreement between predicted and actual results seems extremely good.

TABLE I.- CHARACTERISTICS OF THE BOEING S-307 AIRPLANE

Design gross weight, lb	45,000
Wing area, sq ft	1486
Wing span, ft	107.25
Mean aerodynamic chord, ft	13.9
Slope of lift curve, per radian	4.66
Aspect ratio	7.8
Maximum level-flight speed at 16,000 ft, mph	250
Limit load factor, g	3.25
Ultimate load factor, g	
Positive	4.88
Negative	-1.88

TABLE II.- SUMMARY OF V-G RECORDS SUPPLIED FOR ANALYSIS

	Number of records	Total flight hours	Average flight hours per record, τ
Records supplied by PAA	311	17,095	-----
Records obtained from pilot check flights	6	27	-----
Records available for analysis	305	17,068	-----
Records having more than 120 flight hours	29	4,415	-----
Records used in the analysis	276	12,647	-----
Prewar operation	83	2,386	29
War operation	193	10,261	53
War operation			
Season I	28	1,623	58
Season II	37	2,303	62
Season III	75	3,761	50
Season IV	53	2,574	49



TABLE V
SUMMARY OF OPERATING CHARACTERISTICS OF S-307 AIRPLANE FOR
PREWAR AND WAR OPERATION AND FOR SEASONAL OPERATION
WITHIN THE WAR PERIOD

	Average time (in thousands of hours) to exceed:-		Probable airspeed (mph) (b)
	Limit-load-factor increment, 2.25g (a)	Maximum level-flight speed, 250 mph	
Prewar operation	110,000	160	145
War operation	50	8.4	165
War operation			
Season I	5.7	5.5	170
Season II	170	6.2	165
Season III	900	11.0	155
Season IV	300	4.5	165

^aOne positive and one negative acceleration increment.

^bAirspeed at which the largest accelerations will probably be experienced.

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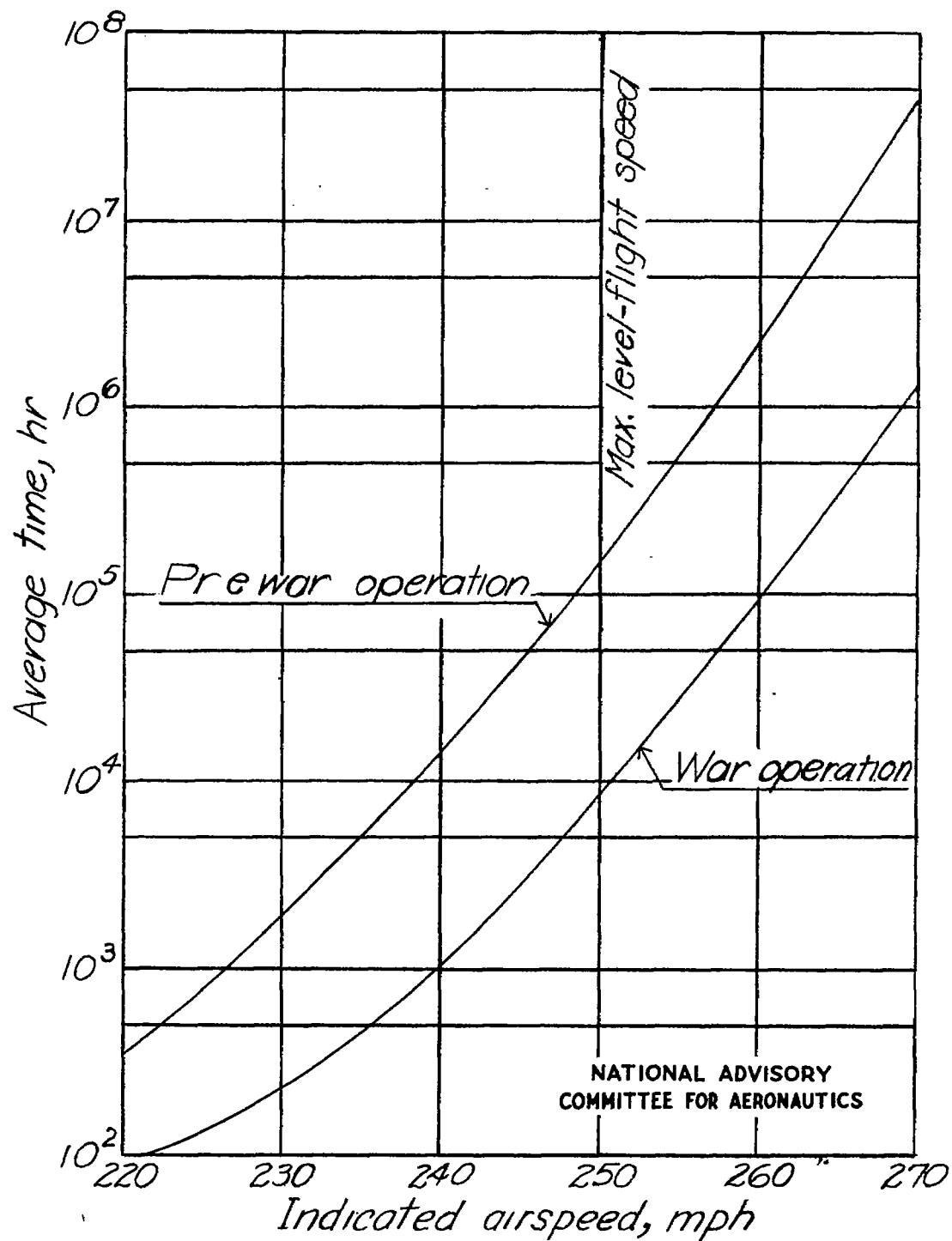


Figure 1.- Average time required to exceed a given value of airspeed. Prewar and war operation.

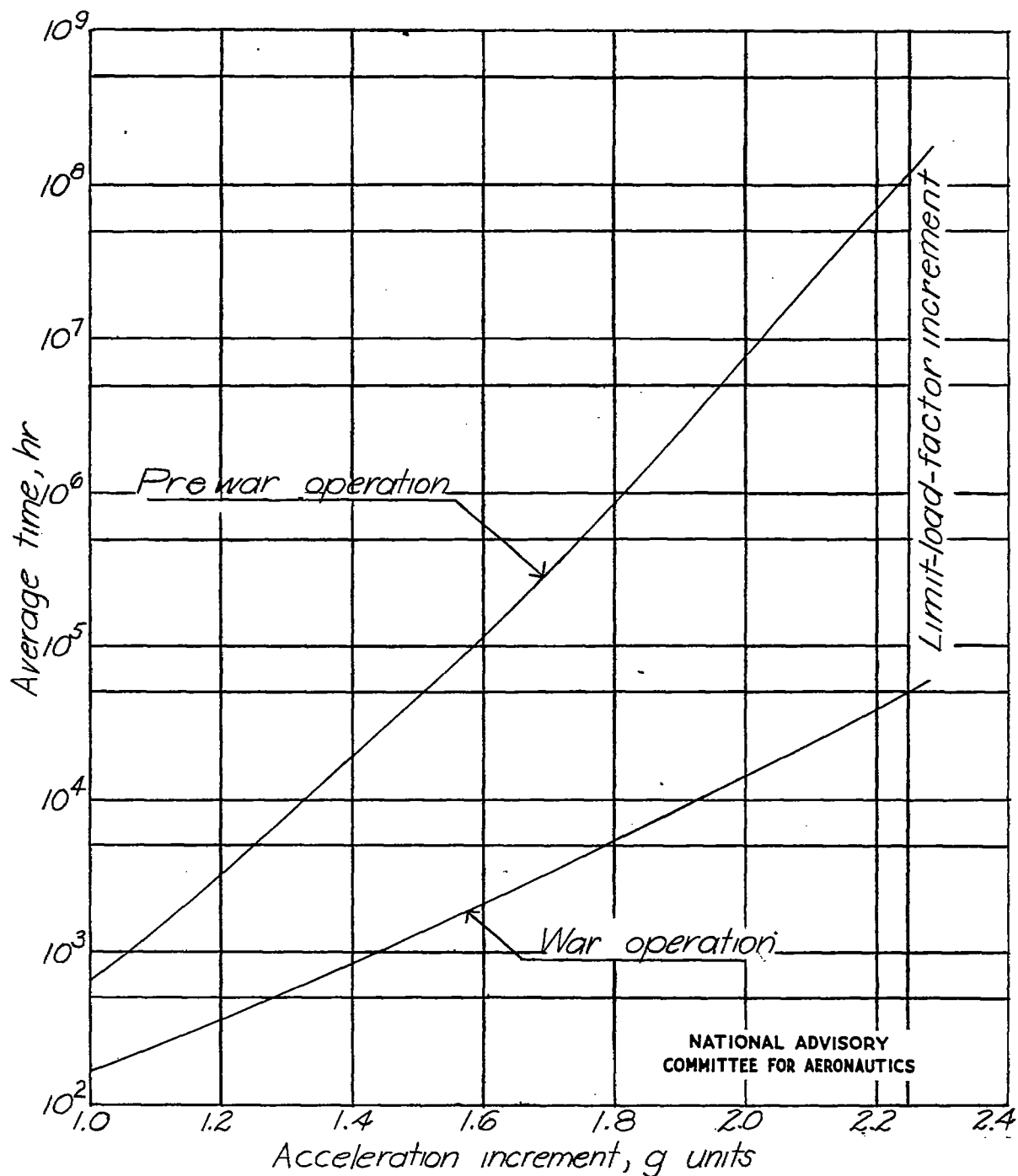


Figure 2.- Average time required to exceed a given value of acceleration.
Prewar and war operation.

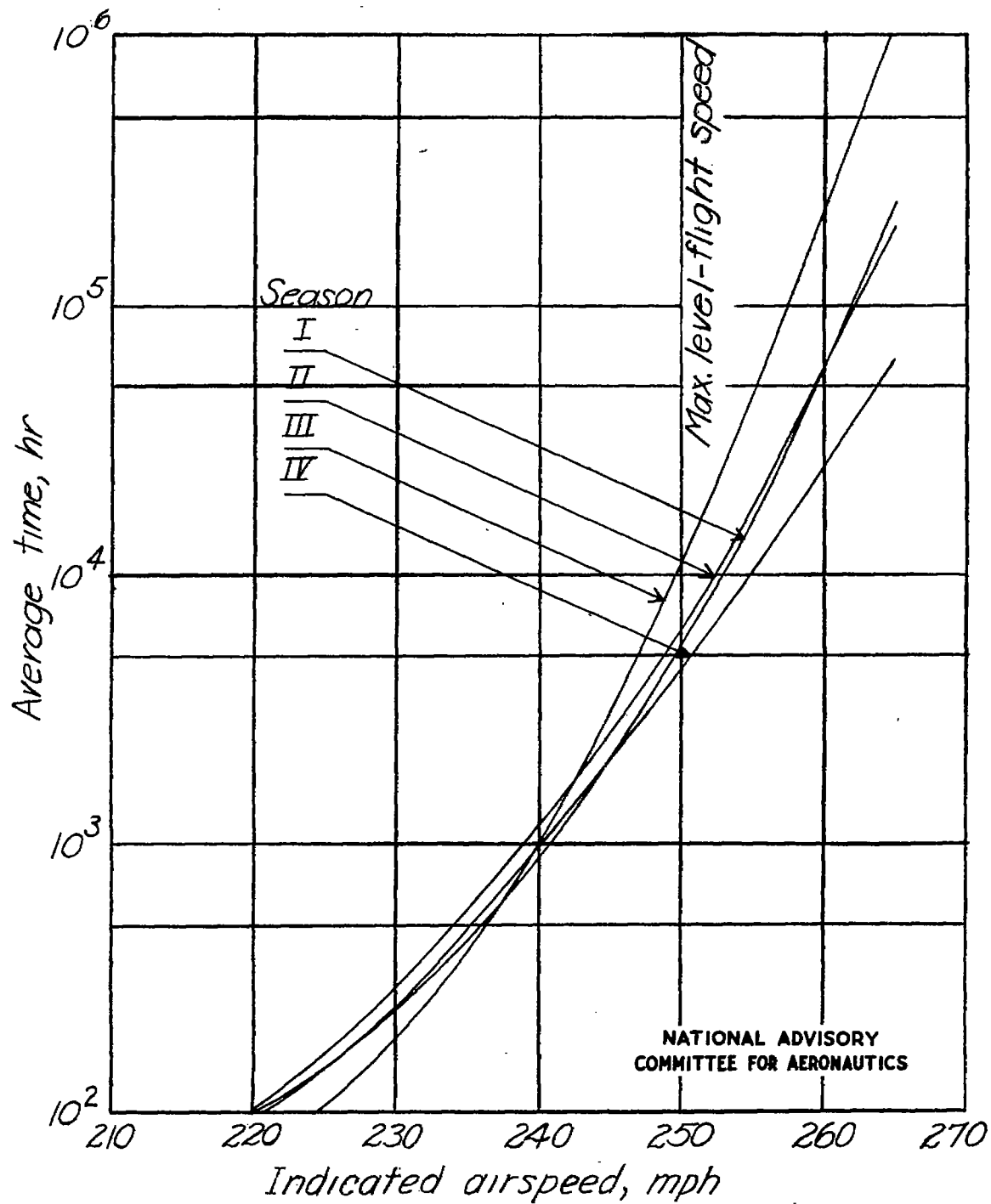


Figure 3. - Average time required to exceed a given value of airspeed. Seasonal operation within the war period.

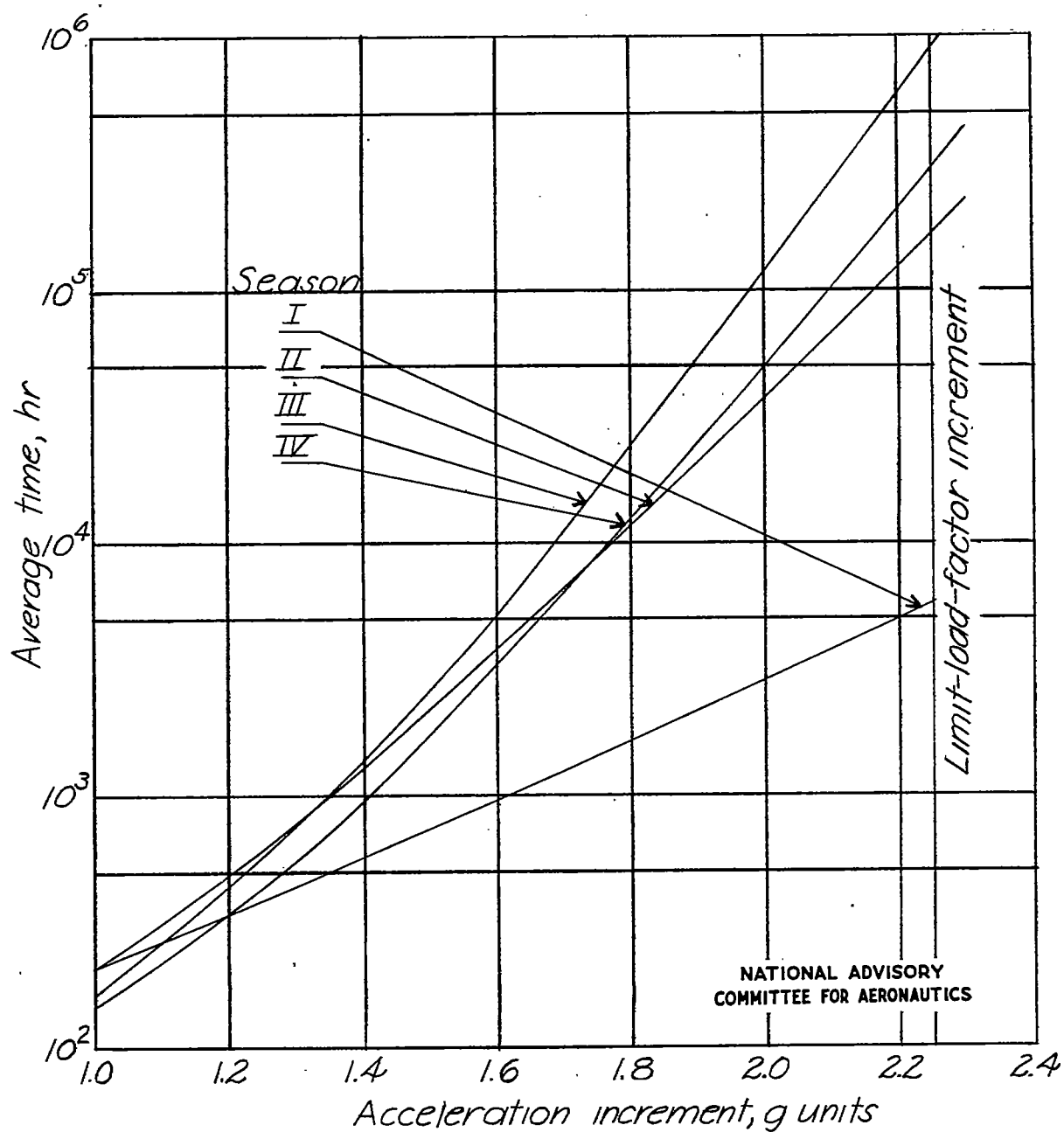


Figure 4.- Average time required to exceed a given value of acceleration. Seasonal operation within the war period.

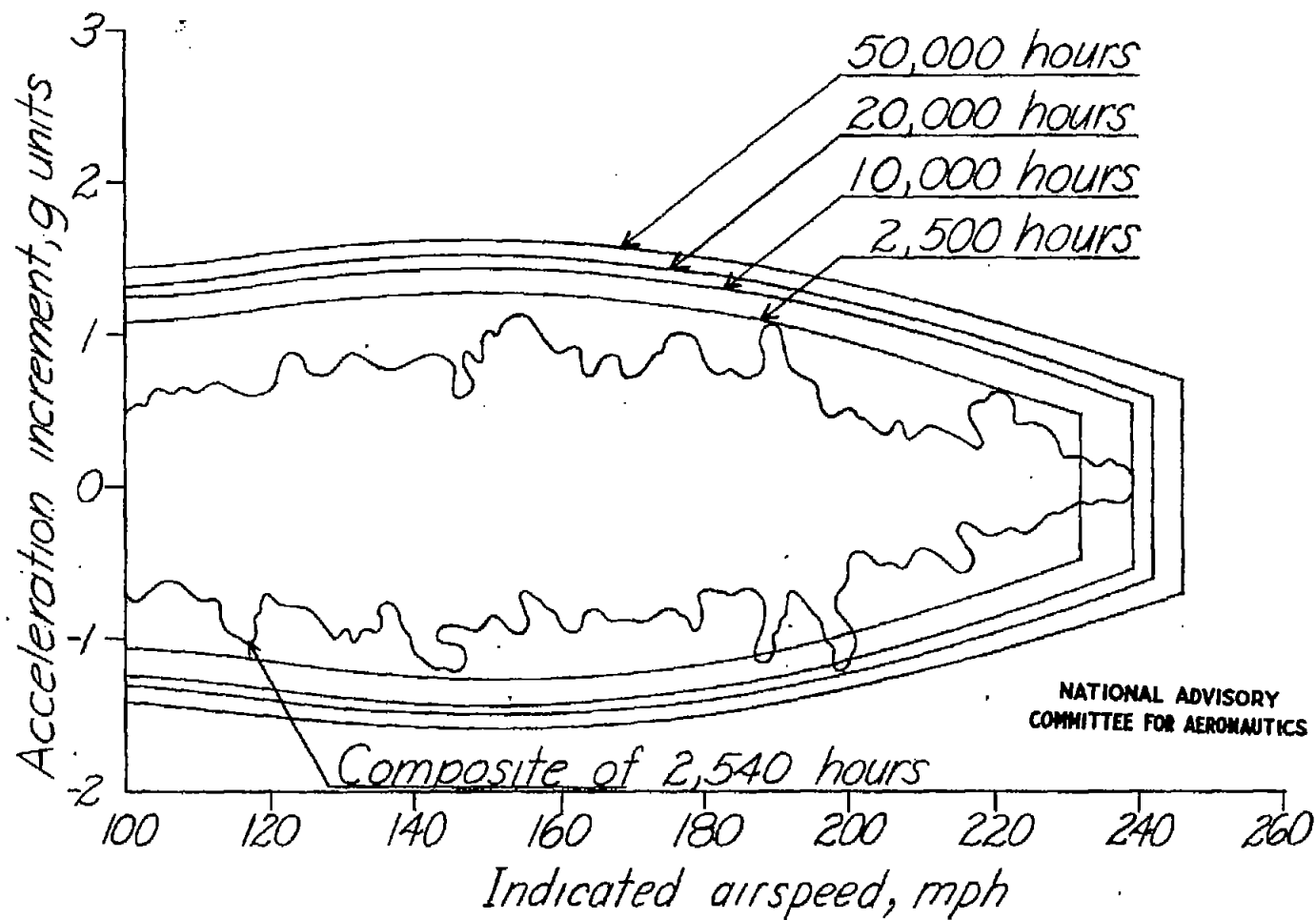


Figure 5.- Comparison of calculated flight envelopes with composite of V-G envelopes obtained in operation during prewar period.

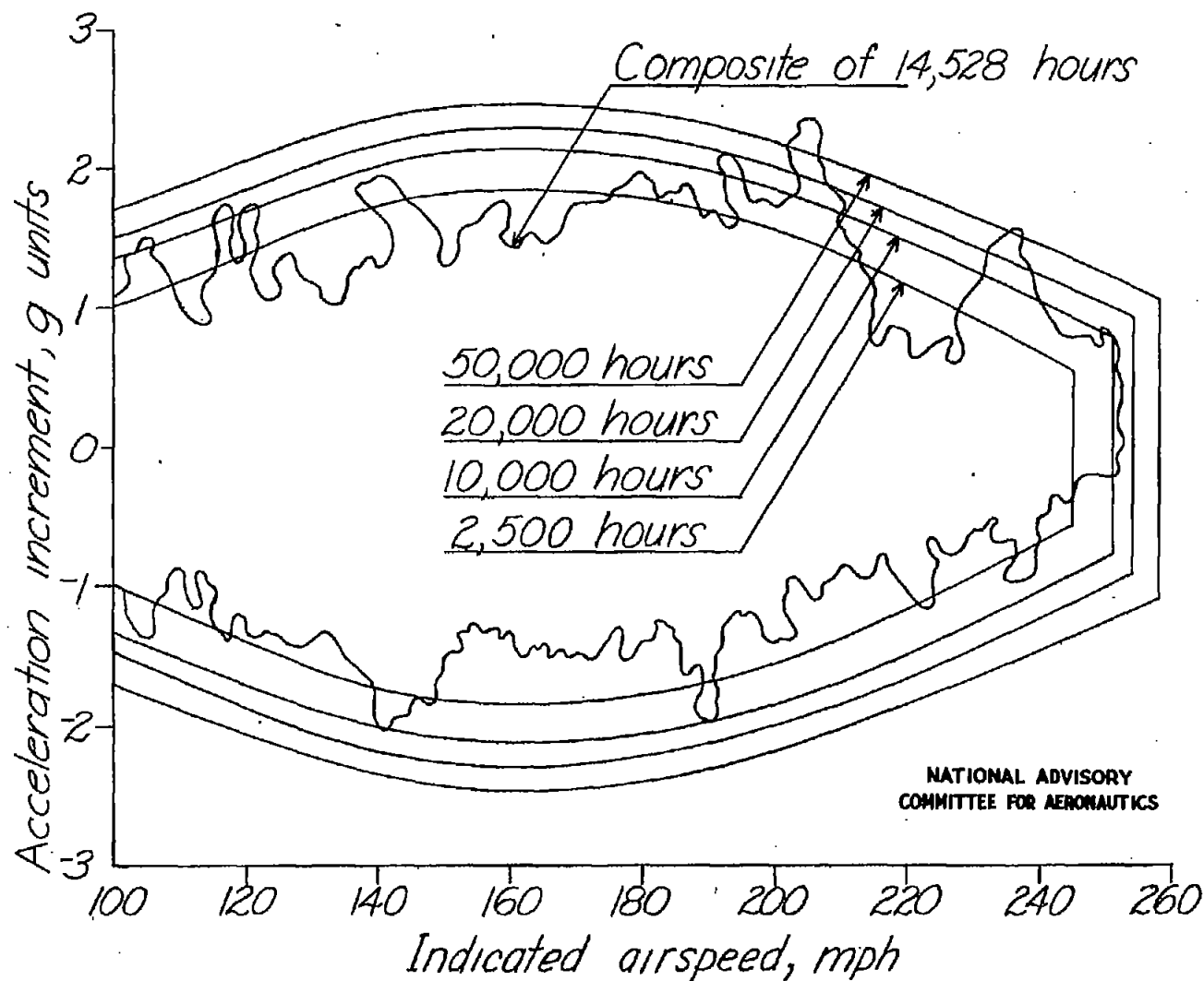


Figure 6.- Comparison of calculated flight envelopes with composite of V-G envelopes obtained in operation during war period.

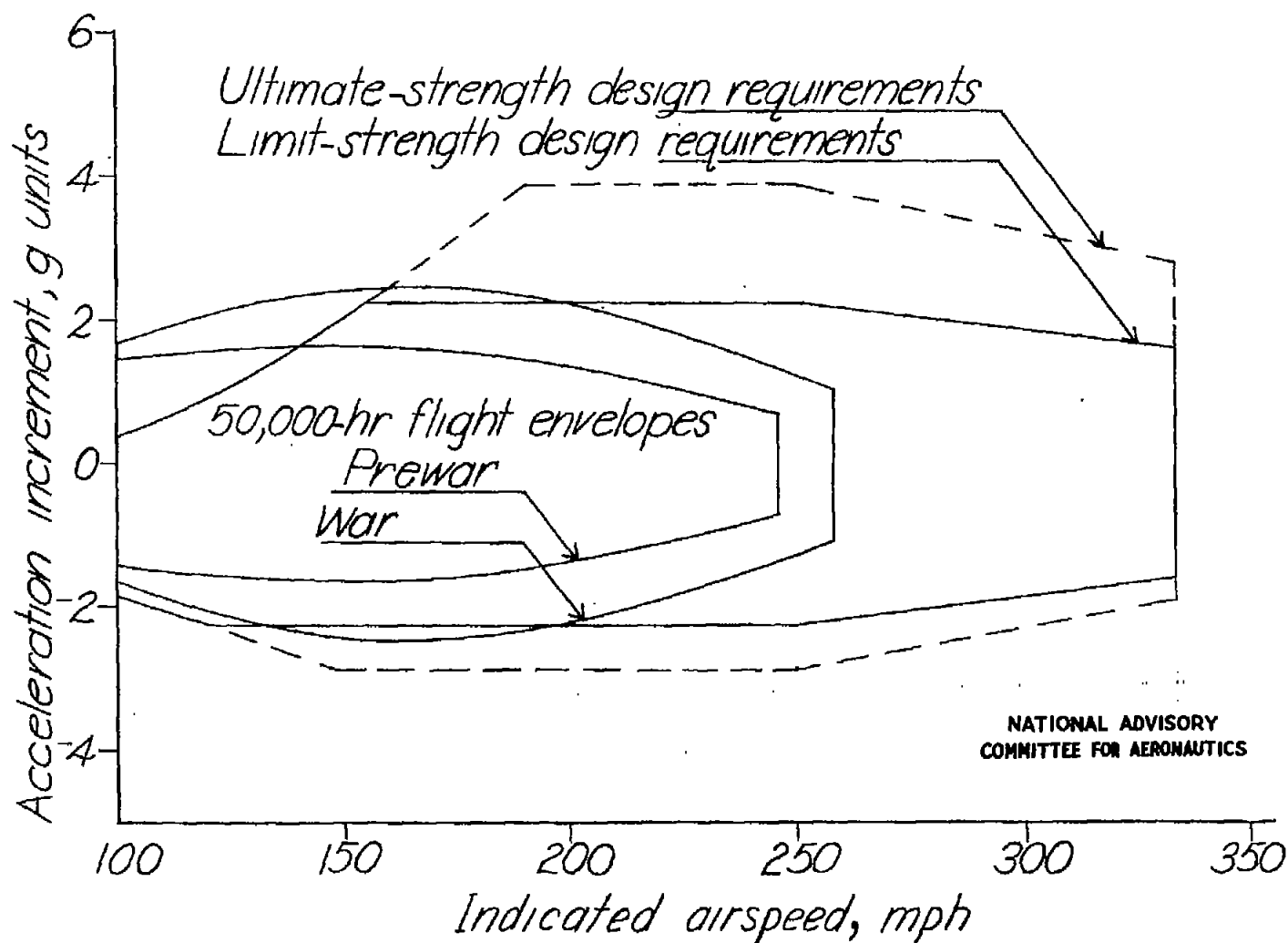


Figure 7.- Comparison of 50,000-hour flight envelopes for prewar and war operations with envelope of design requirements for S-307 airplane.

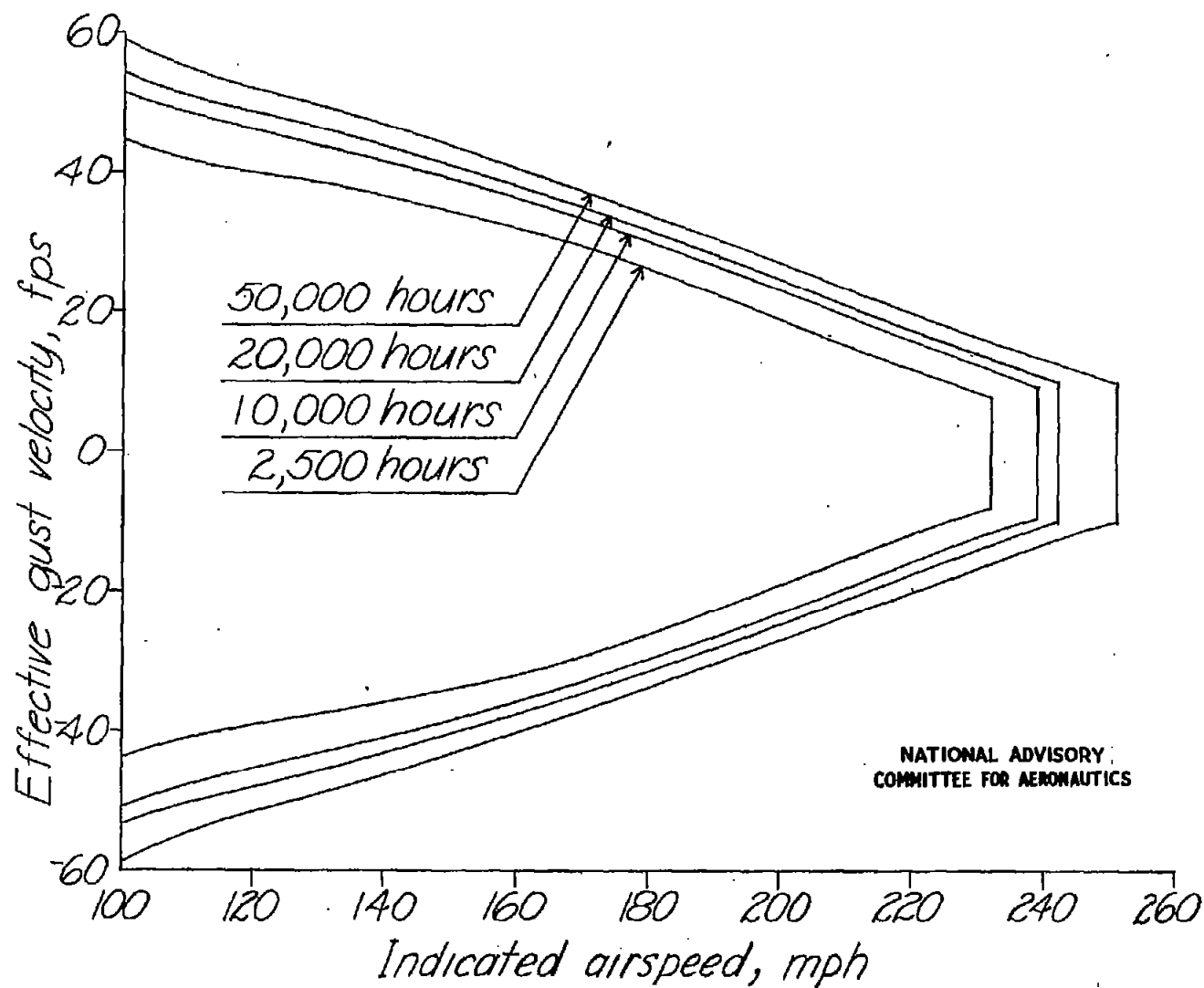


Figure 8.- Effective-gust-velocity envelope for prewar operation.

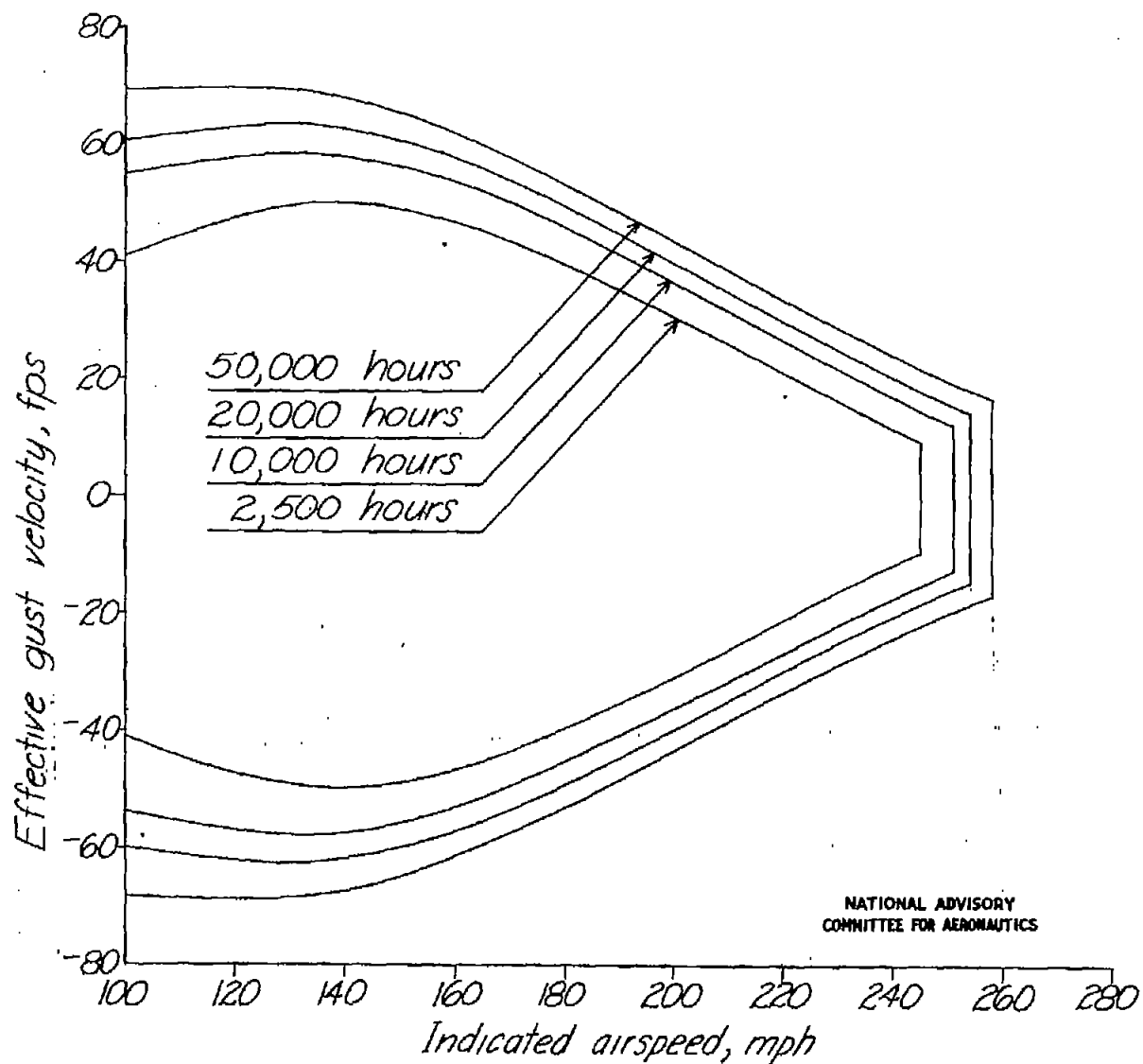


Figure 9.- Effective-gust-velocity envelope for war operation.

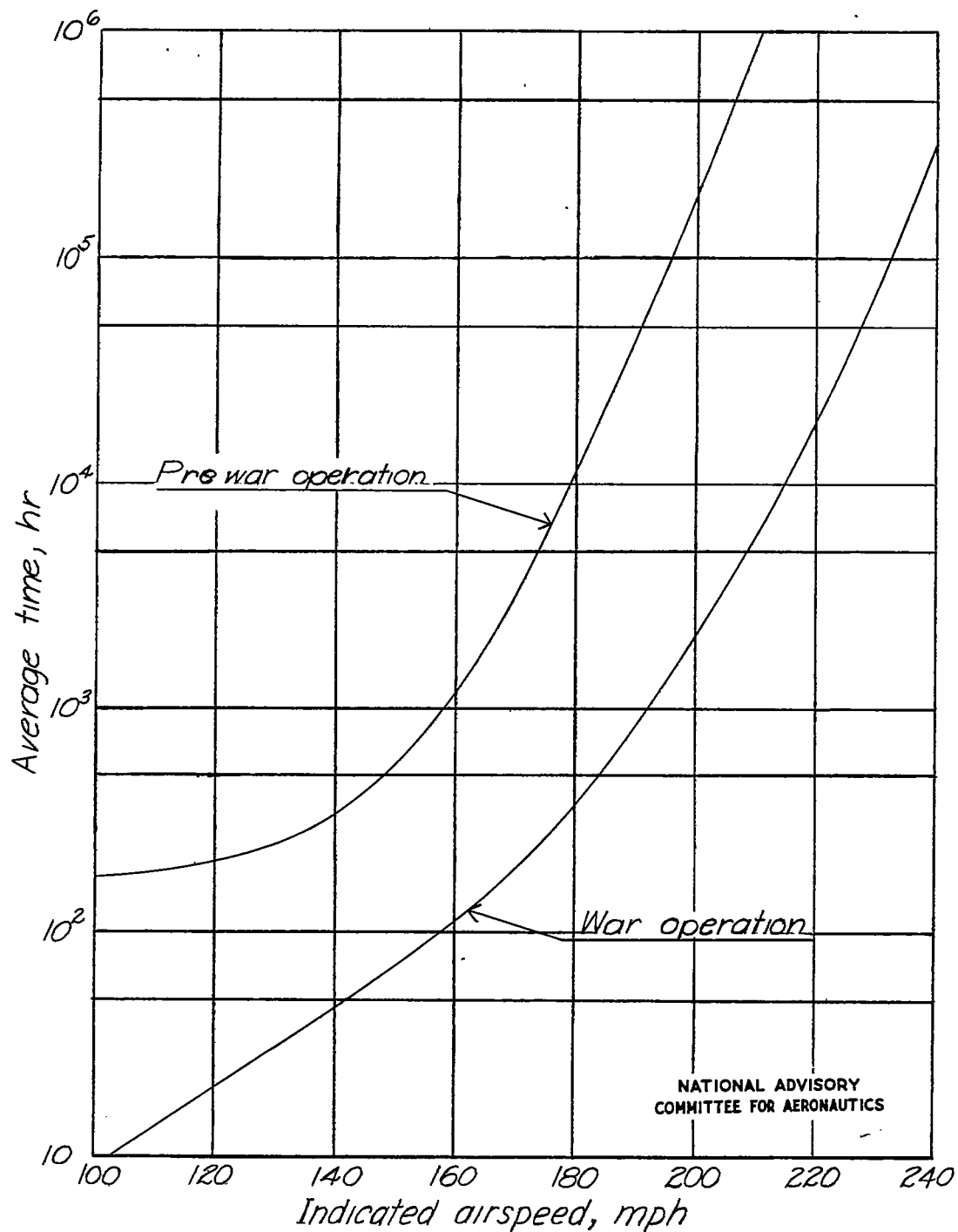


Figure 10.- Average time required to experience an effective gust velocity greater than 30 feet per second at different airspeeds. Prewar and war operation.

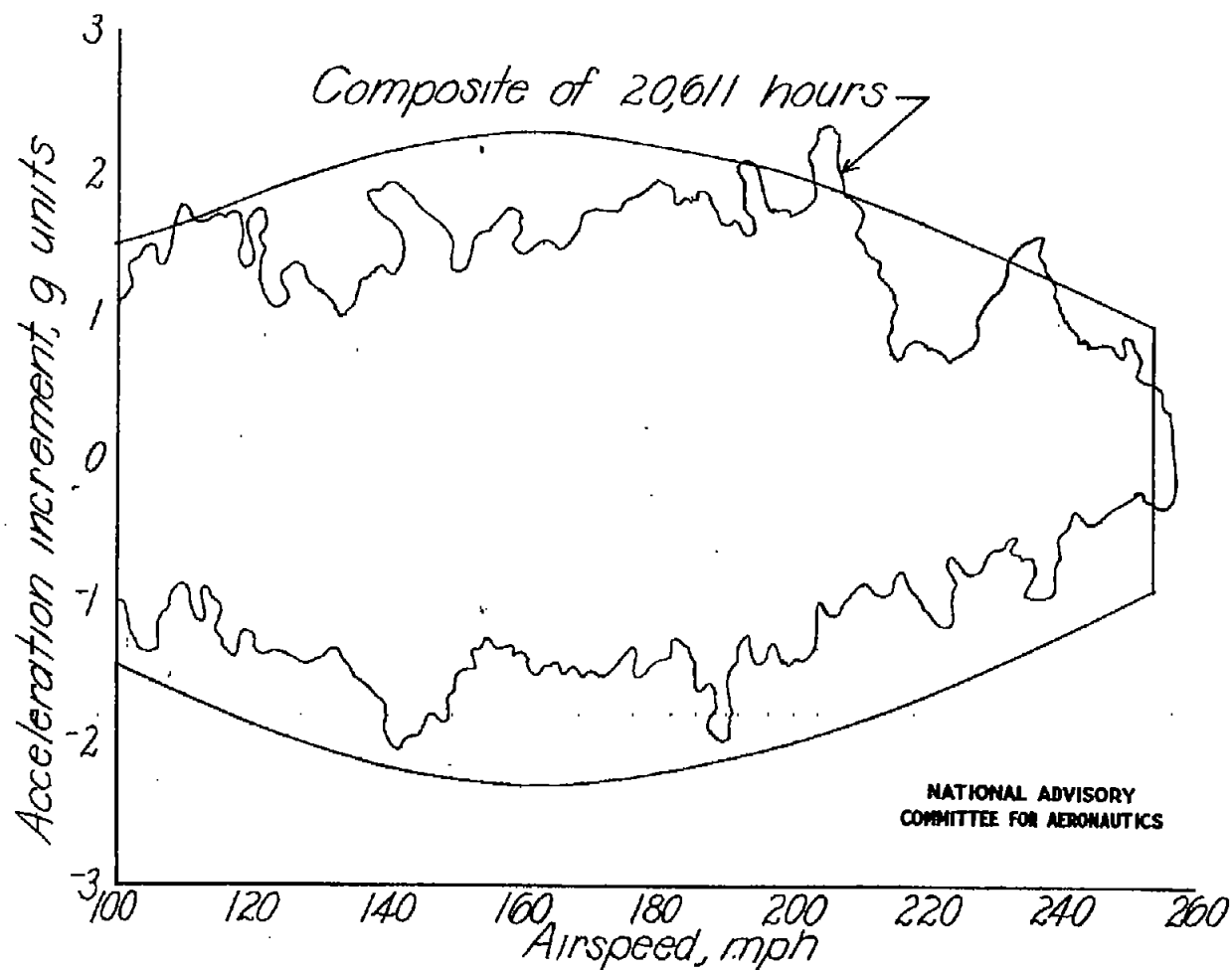


Figure 11.- Comparison of calculated flight envelope for 20,000 hours with composite of all available V-G envelopes for war-time operation.